Algorithm Theoretical Basis Document (ATBD) for the Conical-Scanning Microwave Imager/Sounder (CMIS) Environmental Data Records (EDRs)

Volume 7: Cloud EDRs
Part 3: Cloud Base Height EDR

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RELATED CMIS DOCUMENTATION

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Title	Version	Authorship	Date
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Title		Covering
ATBD for the CMIS TDR/SDR Algorithms		
ATBD for the CMIS EDRs	Volume 1: Overview	Part 1: Integration
		Part 2: Spatial Data Processing • Footprint Matching and Interpolation • Gridding • Imagery EDR
	Volume 2: Core Physical Inversion Module	
	Volume 3: Water Vapor EDRs	Atmospheric Vertical Moisture Profile EDR Precipitable Water EDR
	Volume 4: Atmospheric Vertical Temperature Profile EDR	
	Volume 5: Precipitation Type and Rate EDR	
	Volume 6: Pressure Profile EDR	
	Volume 7: Cloud EDRs	Part 1: Cloud Ice Water Path EDR
		Part 2: Cloud Liquid Water EDR
		Part 3: Cloud Base Height EDR
	Volume 8: Total Water Content EDR	
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Bold = this document

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1 Introduction

1.1 Purpose

This algorithm theoretical basis document (ATBD) provides the underlying mathematical and theoretical background for Cloud Base Height (CBH) EDR (Environmental Data Record) for the Conical-scanning Microwave Imager/Sounder (CMIS) developed by Atmospheric and Environmental Research, Inc. (AER) in support of the National Polar-orbiting Operational Environmental Satellite System (NPOESS).

Clouds are major players in the energy exchanges that regulate the Earth's climate. Infrared radiative transfer is one mechanism by which clouds exchange energy. A cloud layer will absorb infrared radiation emitted by the surface and atmosphere below the layer and will emit radiation downward toward the surface, acting like a thermal blanket to trap heat near the surface. The balance of heat exchange between the surface and the cloud is strongly affected by the height of the cloud base, which relates to the temperature and radiative power of the cloud base. Knowledge of cloud base heights is thus highly useful for climate diagnosis.

The optical properties of the atmosphere are highly dependent on clouds. The operations of aircraft and airborne electro-optical systems often depend on whether there is a clear line of sight from the aircraft to the ground. Planning of operations may therefore depend on a knowledge of cloud base height in relation to the height at which the system will be operating.

1.2 Scope

The Core Physical Inversion Module of the CMIS EDR algorithms performs a major portion of the retrieval processing for the CBH EDR. That module is described in ATBD Vol. 2, which includes discussion of some aspects of the physics of the retrieval problem.This document discusses physical aspects specific to CBH retrieval, presents the portions of the algorithm not covered by the Core Module volume, and presents performance for the CBH EDR product.

2 Overview and Background Information

2.1 Objectives of the CBH EDR retrieval

The CBH EDR algorithm has the objective of deriving CBH reports from CMIS sensor data on a global basis in all weather conditions where clouds are present.

2.2 Summary of EDR requirements

2.2.1 Requirements from System Requirement Document

The text below and Table 2-1 are the portions CMIS System Requirements Document (SRD) section 3.2.1.1.1.1 that apply directly to the CBH algorithm.

Cloud base height is defined as the height above ground level where cloud bases occur. More precisely, for a cloud covered Earth location, cloud base height is the set of altitudes of the bases of the clouds that intersect the local vertical at this location. The reported heights are horizontal spatial averages over a cell, i.e., a square region of the Earth's surface. If a cloud layer does not extend over an entire cell, the spatial average is limited to the portion of the cell that is covered by the layer. As a threshold, only the height of the base of the lowest altitude cloud layeris required and objective is to report cloud base height for all distinct cloud layers.

Table 2-1: Cloud Base Height SRD Requirement Table.

Para. No.		Thresholds	Objectives
C40.4.1-1	a. Horizontal Cell Size	25 km	10 km
C40.4.1-2	b. Horizontal Reporting Interval	25 km	10 km
C40.4.1-3	c. Horizontal Coverage	Global	Global
	d. Vertical Cell Size	N/A	N/A
C40.4.1-4	e. Vertical Reporting Interval	Base of lowest cloud layer	Base of all distinct cloud layers
C40.4.1-5	f. Measurement Range	0 - 15 km	0 - 30 km
C40.4.1-6	g. Measurement Uncertainty	2 km	0.25 km
C40.4.1-7	h. Mapping Uncertainty	5 km	1 km
C40.4.1-8	i. Swath Width	1700 km (TBR)	3000 km (TBR)

2.3 Physics of Problem

There is no passive microwave signal directly associated with the cloud base height. Microwave radiation is indirectly related to cloud base by way of sensitivity to the amount of cloud mass in the atmosphere. The theoretical basis for detecting cloud ice and liquid is discussed in Parts 1 and 2, respectively, of this ATBD volume.

The signal from ice clouds depends on scattering of radiation by ice particles. That process is not directly dependent on the altitude of the cloud. There is some indirect dependence, however, when the scattering is detectable at microwave frequencies where absorption by water vapor is significant, such as near the 183-GHz water vapor line. The cloud scattering signal can be somewhat attenuated by water vapor that overlays the cloud and, all other factors being equal, the attenuation is greater for a lower cloud that has more water vapor above it. One difficulty is that the radiometric data do not provide enough information to have high skill in distinguishing the cloud optical properties from the optical properties of the overlaying layer. Another difficulty is that the information associated with cloud height is not specific to the height of the cloud base, but is aligned with what might be called the effective scattering center of the cloud. That center is weighted toward heights within the cloud where scattering is strongest: where concentrations of ice water mass are greater and particle sizes are larger. It is beneficial to cloud base retrieval skill that cirrus clouds tend to have their largest ice water concentrations and particle sizes near cloud base.

For liquid water clouds, the primary phenomenon for microwave remote sensing is absorption and emission of radiation. The degree of “screening” of the cloud signal by overlaying water vapor (for 183-GHz channels) or oxygen (for 60-GHz-band channels) provides some information on cloud altitude (Wilheit and Hutchison, 2000). Thermal contrast can provide additional information regarding the altitude of cloud water. When the atmospheric temperature decreases with altitude, as it usually does in the troposphere, the emitting temperature of clouds decreases with increasing cloud altitude. This effect is mitigated, however, by the fact that the absorption coefficient of the cloud decreases with temperature (Lipton, et al., 1999). A higher cloud, therefore, has a lower temperature of emission but transmits more radiation from the warmer layers below. In most cases, the net effect is a decrease in microwave brightness temperature with increasing cloud height, but the height signal is not as strong as it would be if the absorption coefficient were independent of temperature. The height signal, however, is related more to the cloud top than to the cloud base. For optically thick clouds the signal is primarily from the cloud top and for optically thin clouds it is from an effective average height of the cloud mass. Non-precipitating clouds are optically thin at frequencies below about 60 GHz. The heaviest of non-precipitating clouds (cloud liquid water > 0.3 kg/m^2) are moderately optically thick at 89 GHz.

While the microwave signals related to cloud height are weak, there is also considerable radiometric ambiguity between cloud height and other environmental variables, particularly cloud liquid water and water vapor amounts. The signals for water vapor cloud liquid and are sensitive to the emissivity of the surface, as discussed in ATBD Volume 2 and Part 1 of this volume. When the signal is larger, as for ocean surfaces, the ambiguities are more readily resolved and the cloud height signal is more discernable by a retrieval algorithm. There is, thus, greater potential skill for CBH retrieval over oceans than over land.

One additional way to reduce the ambiguity between cloud water content, top height, and thickness is to provide ancillary information, from a source other than CMIS, about any of these parameters. Cloud top temperature and pressure can be retrieved from VIIRS infrared data and provided as a constraint to a microwave algorithm.

In precipitating clouds, there is no direct microwave signal from cloud base and even the statistical relationship is very weak. However, there is not a large climatological variation in the base height of precipitating clouds in relation to CMIS requirements, so mere detection of precipitation provides a reasonably reliable indicator of cloud base height.

2.4 Instrument Characteristics

The primary channels for cloud base height retrievals are the vertical and horizontally polarized window channels at 18, 36, and 89 GHz along with the channels on the water vapor lines at 23 GHz and 183 GHz. The 50-GHz channels provide temperature profile information that assists in identifying thermal signals of clouds at the other frequencies.

2.5 Requirements for cross sensor data

The CBH algorithm requires VIIRS cross-sensor SDR longwave infrared window channel data to perform a test for cloud field inhomogeneity. The algorithm also requires EDR data for cloud cover to indicate the presence of cloud and EDR data for cloud top pressure to constrain the CBH solution. The algorithm is adaptable to use cloud top temperature data instead of cloud top pressure, in case there is an algorithm execution conflict wherein the VIIRS EDR algorithm depends on CMIS products to convert from cloud top temperature to cloud top pressure.

2.6 Requirements for External Data

The only external data required to achieve threshold performance for the CBH EDR is surface pressure, derived from combination of NWP model forecast data, and terrain heights from a high-spatial-resolution global topography database.

2.7 Summary of Derived Requirements on the EDR Algorithms

For CBH retrieval in non-precipitating conditions, the algorithm requires cloud top pressure and cloud thickness, in terms of pressure, from the Core Module. It also requires cloud ice water path and cloud liquid water path to indicate the presence of cloud. Profiles of temperature and water vapor are required from the core module to diagnose cloud base for cirrus clouds and to convert cloud base pressure to cloud base height. For the latter purpose, surface pressure is also required. The CBH also requires a flag from the precipitation module (ATBD Vol. 5) indicating the presence of precipitation.

3 Algorithm Description

3.1 Historical and Background Perspective of Proposed Algorithm

Little research has been published regarding cloud base retrievals from passive microwave satellite data, presumably because of the highly limited prospects for retrieval skill. Wilheit and Hutchison (2000) evaluated the potential for retrieval by performing experiments using a physical algorithm that minimizes a penalty function, roughly similar to the CMIS core module. Their experiments were made with a simple model of a cloudy atmosphere, where the single cloud layer was assumed to be saturated and the layers above and below cloud had vertically uniform subsaturated humidity. With this model, it is possible to use the water vapor information in the microwave data to retrieve the cloud base since, by definition, the base resides at the bottom of the saturated layer. Such a model is valid only when the cloud uniformly covers the satellite field of view. A great deal of work has been done in the field of numerical weather prediction (NWP) to evaluate the relationship between the cloud cover in a given atmospheric layer and the relative humidity of that layer, when evaluated on the scale of a model grid cell (Nehrkorn and Zivkovic, 1996; Norquist, 1999). There are large uncertainties in that relationship because there may be nearly saturated layers that have no cloud and there may be extensive cloud cover with grid-cell-average relative humidities substantially below saturation. The NWP evaluations are related to the remote sensing problem since NWP horizontal grids may be comparable to the required CBH horizontal cell size (25-km) and the NWP layers may be comparable to (or often even smaller than) the scales resolvable by a microwave sounder.

3.2 Theoretical and Mathematical Description of Algorithm

The primary retrieval function for non-precipitating clouds is performed by the Core Physical Inversion Module. The module retrieves cloud top pressure and cloud thickness simultaneously with the total cloud liquid water and the profiles of temperature and water vapor. In the scattering mode, the core module also retrieves the top pressure, thickness, and water content of ice cloud. The module has an option to use external data, such as from VIIRS, to specify the cloud top. Because of the variability in the cloud/vapor relationship discussed in Sec. 3.1, the core module algorithm does not assume that cloud occurs only in saturated layers or that a layer with cloud must be saturated. No constraints are applied to the relationship between cloud and vapor. Details of the core module are in ATBD Vol. 2.

3.2.1 Precipitating clouds

Precipitating conditions are identified by the precipitation module. When precipitation is present, the cloud base is set to a value of 1 km. This value may be tuned on the basis of climatology of cloud base in precipitating conditions.

3.2.2 Convective conditions

Under conditions of convective clouds, the cloud base is computed as the lifting condensation level, or LCL. The LCL is the level to which an unsaturated but moist parcel of air would have to be lifted in order for it to become saturated by thermodynamic cooling (via dry adiabatic expansion). During lifting the mixing ratio w of the air parcel is conserved. At the point of condensation, however, the parcel's mixing ratio begins to decrease. Thus the LCL is the pressure level at which the mixing ratio first becomes smaller than the mixing ratio of the parcel at its origin.

Mathematically the method for computing LCL is as follows. Let w_0, p_0, and Θ_0 be the mixing ratio, pressure, and temperature of a moist parcel of air at its origin. The mixing ratio w_n at some pressure level n is defined as

$$w_n = 0.622\, e_n / (p_n - e_n)\,, \tag{1}$$

where

$$e_n = e_{s0} \exp[\, -(L/R_v)\,(1/273 - 1/\Theta_n)\,], \tag{2}$$

is the Clausius-Clapeyron relation for the vapor pressure e_n of a parcel of air at level n whose temperature and pressure are Θ_n and p_n, respectively. Poisson's equation for dry adiabatic processes prescribes the temperature Θ_n at level n in terms of p_0 and Θ_0 as

$$\Theta_n = \Theta_0 \left(p_n / p_0 \right)^{0.286} . \tag{3}$$

Equations (1)-(3) prescribe the numerical recipe for computing the mixing ratio w_n at some pressure level n as a function of the mixing ratio, pressure, and temperature of the moist parcel at its origin. The lifting condensation level is simply that level where $w_n < w_0$ for the first time; the LCL cloud base pressure is then p_n. Interpolation is used to assign a value between the computational pressure levels.

Convective conditions may be identified by one of two tests. The first test operates on VIIRS longwave infrared window channel brightness temperatures. When the variance of the brightness temperatures within the CMIS field of view is greater than a threshold, the field of view is considered to have convective clouds. The threshold may be locally tuned, using a lower threshold over water surfaces, for example. The second test operates on the CMIS retrieved temperature profile to detect a lapse rate characteristic of a well-mixed (convective) boundary layer. When the temperature lapse from the surface to 80 mb above the surface is greater than a threshold value, convective cloud conditions are inferred. The threshold is 5 K and is tunable. This latter test is used when VIIRS data are unavailable.

It is possible to augment the CMIS convective-cloud algorithm using multispectral signatures in reflected solar and emitted thermal infrared window and absorption bands between 0.4 and 15 µm. Gustafson et al. (1994) describe an operational Air Force algorithm that detects and types cumuliform and thunderstorm clouds on global scales using the differential multispectral signatures of the GOES and TIROS imagers, whose bands are included in both the VIIRS and CrIS sensors. The algorithms are tunable and can be exploited to augment the CMIS convective-cloud algorithm whenever coincident imager sensor data are available.

3.2.3 Non-convective liquid clouds

For non-convective cases, the cloud base pressure is determined by adding the cloud thickness to the cloud top pressure, using the data supplied by the core module. There is an option to enhance core module performance for these parameters when external (VIIRS) cloud top pressure data are available to provide a constraint on the retrievals. The thickness is treated as an effective thickness of all the liquid cloud layers combined, for application to cases where there are multiple cloud layers.

3.2.4 Cirrus clouds

The cirrus cloud algorithm has two modes. The first mode is activated when the core module (in scattering mode) detects cloud ice water path > 0.3 kg/m^2. This threshold of detection applies to the baseline channel set for retrieving cloud ice water path. If submillimeter channels are available and are used with infrared channels, the threshold will be lower. In this mode, the cloud base is derived in the same manner as for non-convective liquid clouds, but using the ice cloud top and thickness from the core module. The core module does not use VIIRS cloud top data for cirrus clouds because such data does not improve retrieval performance. The core module performs better when it is unconstrained by the VIIRS data, since the microwave data are more sensitive to the lower portions of the cloud (near its base) where the ice water concentrations and particle sizes tend to be largest.

The second mode is applied when the core module retrieves no significant ice or liquid, but clouds are detected by VIIRS. Because of the lack of significant microwave signal associated with thin cirrus clouds, the bases of such clouds are diagnosed from the profiles of temperature and water vapor produced by the core module.

Once the presence of cloud and its top pressure has been established, a determination is made of the relative humidity at the "effective" cloud position with the help of the retrieved temperature and water-vapor profile. As a fallback, the VIIRS retrieved cloud top pressure can be used with a tunable increment to account for the mean cloud thickness. First, the relative humidity RH_{cld} at the cloud top altitude is noted. This denotes the relative humidity at which the satellite-detected cloud exists. It is important to point out that atmospheric water-vapor profiles are not used to detect cloud, but rather to diagnose the local RH environment in which the cloud has formed. Only the VIIRS cloud detection flags specifies the presence of a cloud.

At this juncture it is assumed that RH_{cld} denotes a representative cloud-layer relative humidity. Then, the RH profile is followed downward until the ambient RH drops below the RH cloudy threshold by a "certain tunable amount;" this pressure level is assigned as the cloud base. The difference between cloudy and clear RH values is expressed mathematically as the level where the rate of change of RH with altitude exceeds a tunable threshold. Assuming that the in-cloud relative humidity profile is roughly constant, the in-cloud rate of change dRH/dp is approximately zero. Following the RH profile down, the prescribed cloud base is the level at which dRH/dp turns "noticeably" positive.

In summary, cloud base is assigned as follows. First, the presence of cloud and its top pressure has been established from VIIRS data. Note at this point that $p_{top} < p_{base}$ and that RH_{cld} is greater than RH_{base}. Then, the RH profile is followed downward from p_{top} until $\Delta RH/\Delta p$ satisfies the constraint

$$(RH_{n+1} - RH_n) / (p_{n+1} - p_n) < a , \tag{4}$$

for some pressure level n+1 at or below the cloud effective pressure level n_{top}. In this case,

$$p_{base} = (p_{n+1} + p_n) / 2, \tag{5}$$

where $2 < n+1 < n_{top}$. A quality flag Q_{flag} is also computed, and is defined as

$$Q_{flag} = (\Delta RH / \Delta p) / a , \tag{6}$$

where $\Delta RH/\Delta p$ is given by the left side of Eq. (4). Under these conditions, $Q_{flag} \geq 1$. The larger the quality flag, the more confidence there is that the dRH/dp threshold constraint has been exceeded. If the RH lapse-rate threshold a is not exceeded in the profile but there is a negative layer-minimum in $\Delta RH/\Delta p$, i.e.,

$$a < (RH_{n+1} - RH_n) / (p_{n+1} - p_n) < 0 , \tag{7}$$

for some layer n+1 at or below level n_{topc}. For the layer where the absolute value of $\Delta RH/\Delta p$ is a maximum (i.e., where $\Delta RH/\Delta p$ is a minimum), the cloud-base pressure is computed using Eq. (5) and the quality flag is defined by Eq. (6); in this case, however, $0 < Q_{flag} < 1$.

The parameter a in the above equations is a tunable threshold that can be derived using long-term comparisons between coincident radiosonde/cloud-base observations. This approach has a practical limitation imposed by the vertical resolution of the CMIS water-vapor sounding. Although satellite water-vapor-profile retrievals have better horizontal spatial resolution than, say, a global NWP model, they lack good vertical resolution. The granularity of the cloud-base pressure is controlled by this vertical resolution and cannot be expected to be any better than within 2 km of the actual cloud base, assuming that RH is a good indicator of cloud vertical boundaries.

3.2.5 Conversion from pressure to height

The hypsometric equation is solved in a discrete form, as

$$\Delta z_i = \frac{\Theta_{vi} + \Theta_{vi+1}}{2} \frac{R_d}{g} \ln\left(\frac{p_{i+1}}{p_i}\right), \quad z_i = \sum_{i=N-1}^{1} \Delta z_i \,, \quad z_N = z_s,$$

where the index *i* corresponds to one of the core module retrieval levels, Θ_v is the virtual temperature, R_d is the gas constant for dry air, and g is the gravitational acceleration. The summation is applied over all layers from the surface to cloud base.

3.2.6 Algorithm processing outline

The cloud base algorithm tests first for precipitation. If precipitation is absent the algorithm tests for convective conditions and, if so, computes cloud base pressure from the LCL formulation. If conditions are non-convective, the algorithm applies the non-convective liquid cloud algorithm to obtain the cloud base pressure when the core module produced significant retrieved liquid water. If liquid significant liquid was not present but ice was present, the cirrus cloud base pressure diagnosis is performed. If no cloud is detected, no cloud base is reported. When a cloud base pressure has been determined from one of the methods it is converted to cloud base height as a final step.

3.3 Algorithm Processing Flow

3.3.1 Processing Flow for the CBH algorithm

The processing flow for the CBH algorithm is illustrated in Figure 3-1.

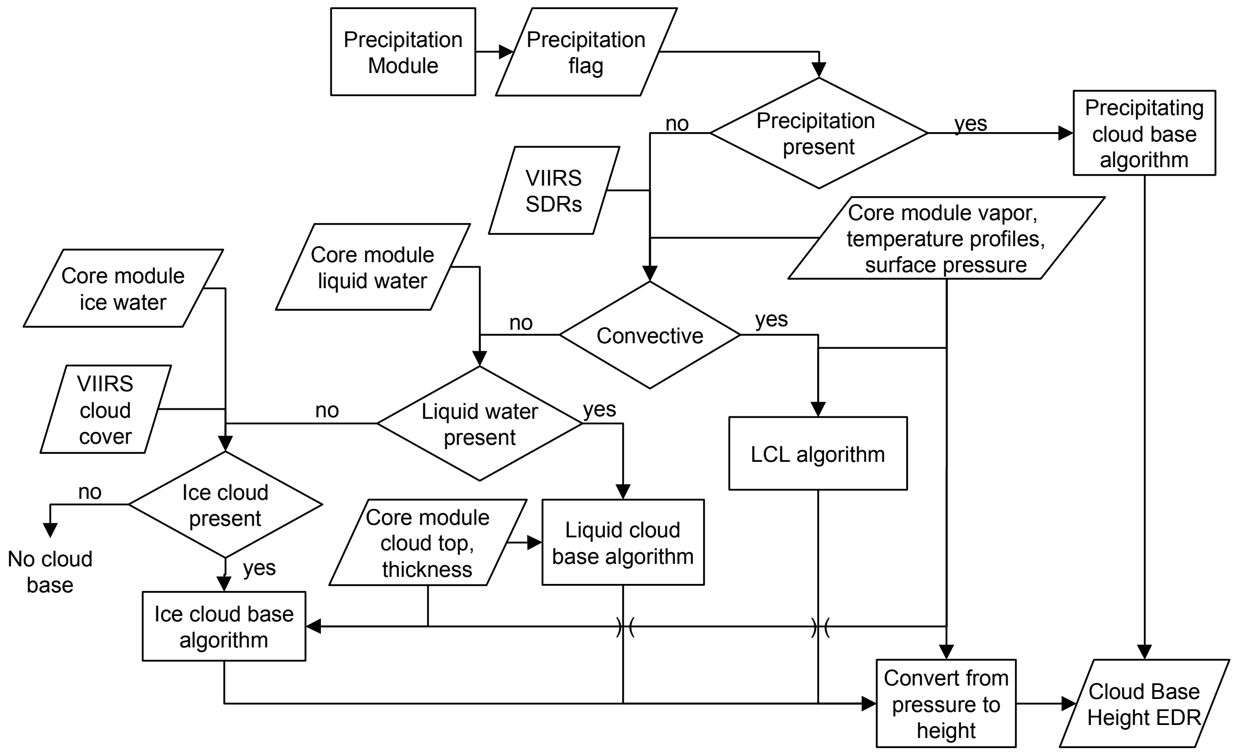

Figure 3-1: Processing flow diagram for the CBH algorithm

3.3.2 Algorithm inputs

Table 3-1: CBH algorithm inputs

Data	Type	Source	Usage
Latitude/longitude at surface	Dynamic, continuous	SDR	EDR reporting
Time/date	"	SDR	EDR reporting
Cloud liquid water	"	Core module	EDR product generation
Cloud top pressure	"	Core module	EDR product generation
Cloud top thickness	"	Core module	EDR product generation
Cloud ice water	"	Core module	EDR product generation
Ice cloud top pressure	"	Core module	EDR product generation
Ice cloud top thickness	"	Core module	EDR product generation
Water vapor profile	"	Core module	EDR product generation
Temperature profile	"	Core module	EDR product generation
Surface pressure	"	Core module	EDR product generation
Quality control parameters	"	Core module	EDR product generation and reporting
Cloud cover	"	VIIRS	EDR product generation
Longwave infrared window channel radiances	"	VIIRS	EDR product generation

3.3.3 Algorithm outputs

Table 3-2: CBH algorithm outputs

Output parameter
Cloud base height
Quality flag
Latitude/longitude at surface
Time/date

3.3.4 Integration of CBH algorithm in the CMIS EDR algorithm set

The CBH algorithm is executed after the core module is executed on 25-km Composite Field of View (CFOV) data.

4 Algorithm Performance

4.1 Description of Test Data and Test Methods

The test data for evaluating the CBH for non-precipitating clouds consist of the data applied to the core module, described in ATBD Vol. 2.

4.2 Performance overview

Performance for the convective cloud algorithm was evaluated by performing simulations where the LCL was computed from the true profile data and compared with the LCL computed from the retrieved profile data. The retrieval errors (Figure 4-1) are larger for land surfaces than for ocean, which is consistent with the trends in errors of the retrieval parameters, low-level water vapor and temperature, that are used in the LCL computation. Some additional retrieval error will be present in convective cases due to the difference between the true LCL and the true cloud base height. An additional 0.5 km error is allocated in the error budget (following section) to account for that error source.

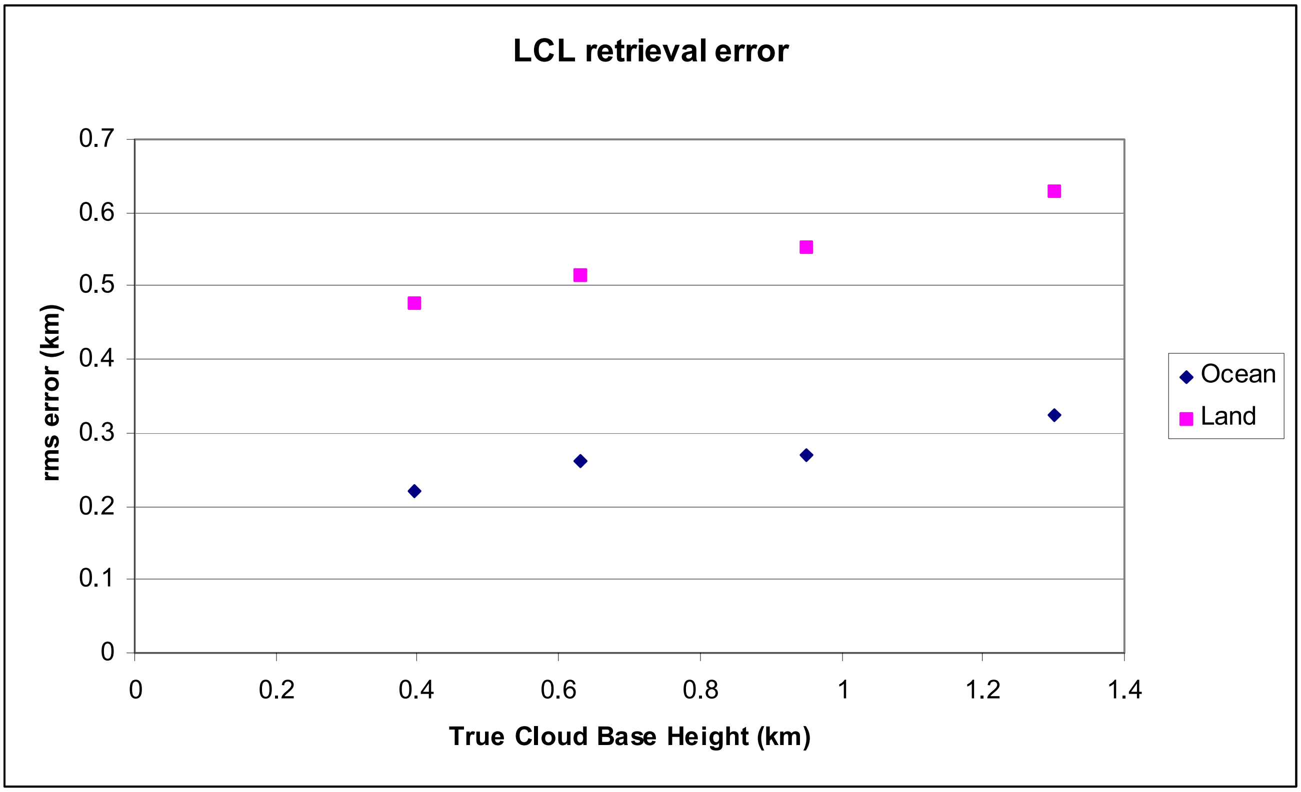

Figure 4-1: CBH rms retrieval error for the LCL computation from core-module-retrieved temperature and water vapor profile data.

Performance for non-convective liquid water clouds was estimated in simulations with the core module and the cloud height computation post-processor. These simulations assumed that VIIRS cloud top data are not available. Simulations where cloud top data were provided by VIIRS had errors that were only lightly better. The performance plot (Figure 4-2) indicates that the surface type (land versus ocean) has no impact for clouds that are far from the surface, but has a large impact for low clouds. Over high-emissivity land surfaces, there is very little microwave sensitivity to cloud liquid, and the cloud base in the core module retrievals tends to stay near the background value of 650 mb. Much of the error for low-altitude clouds is a bias that results from this lack of sensitivity. This bias can be substantially corrected through EDR bias correction. The correction factors are computed by computing the average difference between the true and retrieved CBH, plotted as a function of the retrieved CBH. The degree to which such a bias correction can be effective depends on the skill of the original retrieval, so the proper bias can be selected as a function of retrieved CBH. Figure 4-2 includes results for land cases after a bias correction has been applied, where the worst-bin error has been reduced substantially.

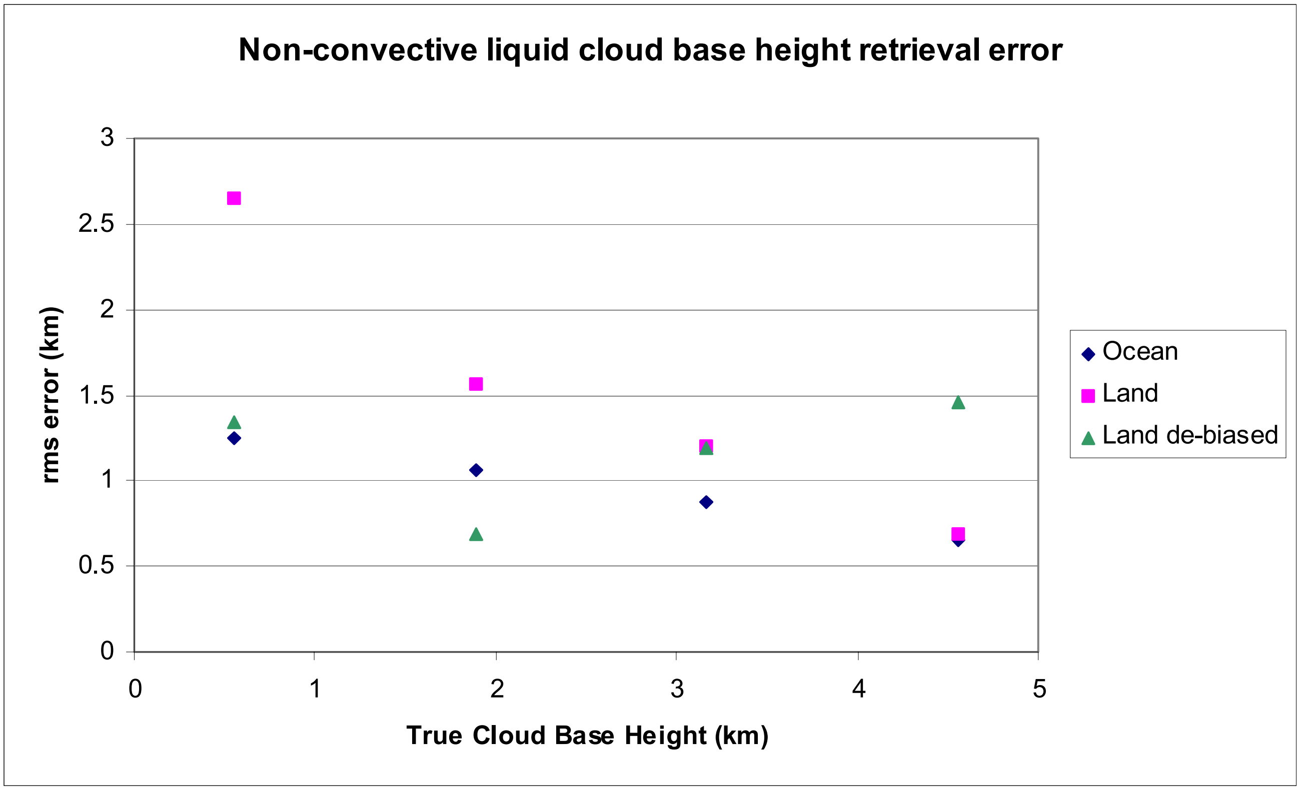

Figure 4-2: CBH rms retrieval error for non-convective liquid water clouds.

For non-convective ice clouds treated with the physical algorithm, the cloud base retrieval error was estimated to be 0.9 km through simulations with clouds that had a variety of distributions of microphysical properties. The simulated cases had true cloud bases primarily at pressures ranging from 470 to 520 mb. To account for larger errors that may occur in the case where the natural global distribution is larger. We estimate the overall error as 1.4 km. For thin cirrus clouds where the cloud height diagnosis is used, we estimate the error to be 2 km.

4.3 Performance summary

The nominal performance for the CBH EDR is summarized in Table 4-1. The error budget is in Table 4-2. The error estimates were made from retrievals performed directly at 25-km CFOV size, under the assumption that the cascade (see ATBD Vol. 1: Integration) would have negligible effect on CBH performance, given that cloud varies on short spatial scales. Performance is computed in bins that span the measurement range and the quoted performance refers to the worst-case bin unless otherwise specified.

Table 4-1: Nominal performance for the CBH EDR.

	Thresholds	Objectives	Performance
a. Horizontal Cell Size	25 km	10 km	≤25 km
b. Horizontal Reporting Interval	25 km	10 km	≤25 km
c. Horizontal Coverage	Global	Global	Global
d. Vertical Cell Size	N/A	N/A	N/A
e. Vertical Reporting Interval	Base of lowest cloud layer	Base of all distinct cloud layers	Base of lowest cloud layer
f. Measurement Range	0 - 15 km	0 - 30 km	≥0 - 15 km
g. Measurement Uncertainty	2 km	0.25 km	≤2 km
h. Mapping Uncertainty	5 km	1 km	≤3 km
i. Swath Width	1700 km (TBR)	3000 km (TBR)	≥1700 km

The row in Table 4-2 denoted "Default retrieval error" refers to the error sources incorporated into the default retrieval simulations, including smoothing (null-space) and radiometric noise. Following that row are several rows (up to "Subtotal") for which the errors are additive. The numbers cited are the added retrieval errors that were found as each error source was individually simulated.

The "default retrieval error" listed in Table 4-2 were derived by combining performance for the various algorithm modes, as summarized in Table 4-3. The "proportion" column indicates the weighting between the conditions which is based on estimates of the global frequency of occurrence of the conditions, while only considering cloudy environments.

Where an error budget entry is zero, that indicates that the error term is negligible in relation to the other terms, not that the error term is identically zero.

The nominal performance includes the effect of fractional cloud cover that occurs in non-convective environments. Cloud cover less than 40% is excluded (see following section). For 50% cloud cover over ocean, the impact on CBH error was found to be about 200 m. Over all nominal conditions, the net effect is estimated to be about 50 m.

Uncertainty in the surface pressure, provided as external data to the core module, was found experimentally to have a very small impact on CBH performance (about 40 m proportional increase in error).

Errors are introduced by the difference in spatial weighting between the horizontal cells used for validation (uniform averaging over a square) and the composite antenna pattern represented by the CFOV. Analysis of this effect is discussed in Appendix TBD of ATBD Vol. 1, Part2: Footprint Matching and Interpolation. These errors are listed as “cell mismatch error” in the budget.

The margin accounts for spectroscopic errors, including residual calibration errors, and channel spatial coregistration errors. It also includes error inflation due to cloud layer complexity, including vertical inhomogeneity of cloud mass within the cloud layer.

Table 4-2: Error (km) budget for CBH EDR

Term	Error
Default core module retrieval error	1.10
Partial cloud cover	0.05
Surface pressure error	0.04
Subtotal	1.19
Cell mismatch	0.20
Net	1.21
Margin	0.8
Total	2.0

Table 4-3: CBH EDR performance (rms error in km) for non-precipitating clouds for various retrieval modes.

Condition	Nominal Proportion	rms Error (km)
Convective Ocean	21%	0.83
Convective Land	9%	1.13
Non-convective liquid, Ocean	25%	1.25
Non-convective liquid, Land	10%	1.46
Non-convective ice, Physical	15%	1.4
Non-convective ice, Thin cirrus	0%	2
Precipitating	20%	0.75
Net	100%	1.09

4.4 Summary of performance under degraded measurement conditions

Performance under degraded measuring conditions is summarized in Table 2-1 and performance exclusions are listed in Table 4-5.

Table 4-4: CBH performance under degraded measurement conditions.

Condition	Measurement uncertainty
VIIRS IR radiances not available and lowest cloud is predominantly ice	3 km

Table 4-5: Exclusions for CBH performance

Condition	Indicator
Partial cover of clouds not identified as cumulus or stratocumulus	Clouds with lowest bases have cloud cover less than 40% of cell and temperature lapse rate from cloud base to surface (1.5 m) is less than 7 K/km
Heavy ice cloud overlays liquid cloud	Cloud ice water path > 0.3 kg/m^2 over liquid cloud layer
Microwave optical depth of the lowest cloud layer is small relative the optical depths of overlaying cloud layers	Cloud liquid water in lowest cloud layer is less than 40% of cloud liquid water in higher cloud layers

4.5 Special considerations for Cal/Val

4.5.1 Measurement hardware

4.5.2 Field measurements or sensors

4.5.3 Sources of truth data

5 Practical Considerations

5.1 Numerical Computation Considerations

5.2 Programming/Procedure Considerations

5.3 Computer hardware or software requirements

5.4 Quality Control and Diagnostics

5.5 Exception and Error Handling

5.6 Special database considerations

5.7 Special operator training requirements

5.8 Archival requirement

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LIST OF ACRONYMS

AER	Atmospheric and Environment Research
ATBD	Algorithm Theoretical Basis Document
CBH	Cloud Base Height
CFOV	Composite Field of View
CLW	Cloud Liquid Water
CMIS	Conical-Scanning Microwave Imager/Sounder
EDR	Environmental Data Record
FOV	Field Of View
IPO	Integrated Program Office
LWP	Liquid Water Path
NPOESS	National Polar-orbiting Operational Environmental satellite System
QC	Quality Control
SDR	Sensor Data Record
SRD	Sensor Requirement Document
SSM/I	Special Sensor Mirowave/Imager
SSM/T-2	Special Sensor Mirowave/Temperature-2
TBD	To Be Determined (by contractor)
TDR	Temperature Data Record
VIIRS	Visible/Infrared Imager/Radiometer Suite